

FANTM: THE FIRST ARTICLE NIF TEST MODULE FOR THE LASER POWER CONDITIONING SYSTEM*

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Abstract

Designing and developing the 1.7 to 2.1-MJ Power Conditioning System (PCS) that powers the flashlamps for the National Ignition Facility (NIF), currently being constructed at Lawrence Livermore National Labs (LLNL), is one of several responsibilities assumed by Sandia National Labs (SNL) in support of the NIF Project. The test facility that has evolved over the last three years to satisfy the project requirements is called FANTM. It was built at SNL and has operated for about 17,000 shots to demonstrate component performance expectations over the lifetime of NIF. The final full NIF system will require 192 PCSs (48 in each of four bays).

This paper briefly summarizes the final design of the FANTM facility and compares its performance with the predictions of circuit simulations for both normal operation and fault-mode response. A physics-based, semi-empirical amplifier gain code indicates that the 20-capacitor PCS can satisfy the NIF requirement for an average gain coefficient of 5.00 %/cm and can exceed 5.20 %/cm with 24 capacitors.

I. FANTM PULSED POWER DESIGN

The FANTM bank consists of 20 (24 max) 86-kJ, nominally 300- μ F capacitors that are operated in parallel near 24 kV. Each capacitor (C in Fig. 1) is isolated from the rest of the bank by a current-limiting damping element (D), which is a 25-m Ω , 9- μ H resistive coil. They connect to a single bus (B) that feeds the gas switch (S). The single ST300A air-insulated switch transfers over 500-kA peak current in a 300- μ s FWHM critically damped pulse from the bank into 20 parallel output lines. Each of these lines is composed of a matched ballast inductor (I), an RG 220/U coaxial cable (L), which is 47.6-m long, and either a dummy resistive load or a pair of series-connected flashlamps. The full NIF will also include modules with a range of output cable lengths from 20 to 55 m, due to the different locations of the PCS modules with respect to the laser amplifiers. The main bank module has a weight of approximately 7 metric tons, a footprint of about 1.52 by

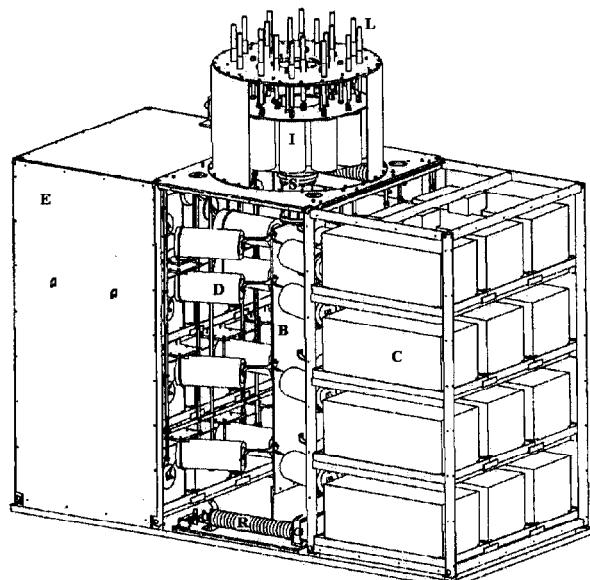


Figure 1. View of uncovered 24 capacitor PCS module.

3.35 m, and a total height of about 3.11 m. A flashlamp pre-ionization pulse from a smaller 50-kJ Pre-Ionization/Lamp Check (PILC) parallel bank precedes the main pulse by a few hundred microseconds.

A. High Energy Capacitors/Damping Elements

The metallized-dielectric, self-healing capacitors are installed in two facing racks, each three capacitors wide and four high. The opening in the frame for each capacitor is 50.8 x 50.8 x 101.6 cm. The capacitors are insulated from the module frame by PVC trays, 0.32-cm thick, with a 5.7-cm lip. The nominal NIF bank is charged in approximately 60 s. The capacitors have an equivalent series resistance of <20 m Ω . The capacitor banks are electrically floating inside a 1-cm thick steel enclosure (E), which is connected to facility ground. The enclosure and vented side panels serve as debris containment for the rare occasions when the large stored energy finds an alternative fault path to ground.

Stainless steel coils with a mean diameter of 11.6 cm and a wire diameter of 1.43 cm serve to protect the capacitors from the rest of the bank for the case of an internal capacitor fault. These are covered by fiber cloth and epoxy reaching about 19.4 cm in diameter and 42.1 cm in length. The damping elements are sufficiently robust to maintain mechanical integrity after a major fault (up to 390 kA); they would not be able to continue

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14. ABSTRACT Designing and developing the 1.7 to 2.1-MJ Power Conditioning System (PCS) that powers the flashlamps for the National Ignition Facility (NIF), currently being constructed at Lawrence Livermore National Labs (LLNL), is one of several responsibilities assumed by Sandia National Labs (SNL) in support of the NIF Project. The test facility that has evolved over the last three years to satisfy the project requirements is called FANTM. It was built at SNL and has operated for about 17,000 shots to demonstrate component performance expectations over the lifetime of NIF. The final full NIF system will require 192 PCSs (48 in each of four bays). This paper briefly summarizes the final design of the FANTM facility and compares its performance with the predictions of circuit simulations for both normal operation and fault-mode response. A physics-based, semi-empirical amplifier gain code indicates that the 20- capacitor PCS can satisfy the NIF requirement for an average gain coefficient of 5.00 O/o/cm and can exceed 5.20 %/cm with 24 capacitors.				
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operating. They attach to the capacitor center conductors and the switch bus with 0.32-cm thick copper straps.

B. High Voltage Bus and Dump Resistors

The vertical bus is a 59.7-cm wide plate of 1.27-cm thick aluminum that tapers near the top to bolt to the lower switch plate. It is supported from the floor by two 1.27-cm G-10 plates. It is connected to the main bank power supply through a charge-isolation circuit. The PCS module includes two independent safety dump assemblies; one is at the top and the other is at the bottom on opposite sides of the bus. Instead of the single long stack (R in Fig. 1), each assembly is composed of two series stacks of eight, 15.2-cm diameter, 2.54-cm thick carbon composition discs from HVR Advanced Components. Each stack is $540\ \Omega$ with a decay time constant of about 3.4 s. A series connected Ross relay, with solenoids requiring ac voltage to open and spring drives for normal closing, provides the fail-safe closure.

C. Output Switch and Trigger Generator

The output switch is a Maxwell PI ST-300A spark gap. It has a steel housing and 7-cm diameter poco-graphite electrodes with an initial gap of 0.32 cm. The switch dielectric medium is dry air, which flows through 5-micron filters. Extensive testing has resulted in a well-known self-break curve and very reliable operation at 40 to 50% of self-break. The air pressure is adjusted according to the predictable gap spacing as the electrodes erode due to the large 145-C charge transfer per shot. The switch end-of-life, as determined by reliable triggering range, occurs near 2,000 shots when the gap has grown to about 2.5 cm, for a total transfer of about 300 kC. The switch maintenance and refurbishment is simple.

The trigger generator for the PCS output switch is a Maxwell PI TG-803-1, which was developed for this application. It uses an SCR for its main switch, pulse-charging an output capacitor through a pulse-transformer to approximately 95 kV. This capacitor is discharged through a sealed gas-filled spark-gap switch and an output blocking capacitor. The generator has a footprint of about 20.3 x 40.6 cm and is mounted on top of the module enclosure. Its high voltage bushing passes through a hole in the top plate. The trigger generator output has a Pulsed Power Components' high-current fuse connected in series before it enters the side of the module output switch via an automotive spark plug. The fast trigger pulse is isolated from the load by a large Ceramic Magnetics' ferrite core at the top of the switch.

D. Ballast Inductors and Output Cables

The set of 20 ballast inductors is attached to a common 1.27-cm thick aluminum plate, which is fed by the output switch through the isolation cores. Copper coils with a mean diameter of 8.87 cm and a wire diameter of 0.65 cm are contained in a fiberglass-reinforced plastic. Fault currents of 100 to 190 kA represent worst-case conditions

that the inductors are designed to survive mechanically, once. The assembly is enclosed by a 1.07-m diameter, top-hat shaped housing on top of the PCS module.

The ballast inductors serve the dual purposes of balancing the currents delivered to each output cable and load for a given module, plus matching the pulse shapes for all of the NIF modules with various cable lengths. The NIF module design calls for $<30\ \mu\text{H}$ of total inductance for the combination of the ballast inductor, cable, flashlamps, and all the transitions and connections. Four different inductance values will probably be used to compensate for the different inductances associated with four different ranges of cable lengths as shown in Table 1.

Table 1. NIF ballast inductor single-pitch design.

Inductance(μH)	No. Turns	Cable Range(m)
19.1	25.5	19.8 – 27.7
17.5	23.5	27.7 – 38.1
14.3	19.5	38.1 – 48.2
12.8	17.5	48.2 – 54.9

Each NIF module will drive a set of 20 RG-220 coaxial cables and 20 flashlamp pairs. A double-braid outer conductor configuration will be used for cables shorter than about 38 m, and a triple-braid outer conductor configuration will be used for higher loss cables longer than 38 m. Most of our testing on FANTM has been with triple-braid cables that are 47.5 m long. It was decided to allow for voltage adjustments on every module to achieve the best matching of performance. The gain improvement can be accomplished also through hand-selection of higher-capacitance cans for the higher loss modules, or by adding a capacitor to the baseline bank of 20.

E. Resistor Loads and Flashlamp Loads

The dummy load assembly consisted of 20 independent floating resistor stacks. The 2- μH stacks were composed of five carbon composition discs from HVR Advanced Components that produced an average of $412\ \text{m}\Omega \pm 4\%$ per stack, about 14% lower than the expected lamp operating resistance. They were air-cooled with large blower units to maintain a steady operating temperature. By the end of their 7,200-shot series the interface contacts were degrading, and several stacks had to be replaced.

The FANTM facility includes 40 flashlamps uniquely designed for the NIF application. They are housed in an air-cooled aluminum cabinet that roughly simulates the lamp cassette on NIF. The xenon-filled lamps are 1.8 m long with a diameter of 4.3 cm. Their nominal resistance at peak current and gain is $476\ \text{m}\Omega \pm 8\%$. Lamp variations result in significant amplitude and timing spreads.

F. PILC Module

The PILC bank and associated hardware are in a separate 0.61 by 1.52 by 1.98-m high cabinet adjacent to the PCS module. It is connected through the PCS top-hat assembly with a series isolation resistor and an RG 220

coaxial cable, which should have a double or triple shield braid for fault tolerance. Typically, three parallel, inductively-isolated capacitors are discharged by a single air-insulated switch into the same load path seen by the PCS main bank. The nominal circuit values are 130 μ F of capacitance driving a net series inductance of approximately 3.2 μ H with a net series resistance of about 100 m Ω . Variations of this circuit can be charged from 24 to 28.5 kV to deliver between 500 and 700 kJ to each flashlamp. Like the main bank module, the PILC module is contained in an EMI enclosure with the pulsed power system electrically floating relative to the enclosure. The enclosure is tied to the facility ground, and the pulsed power ground is connected to the PCS pulsed power ground through the shield of the output coaxial cable.

II. FANTM PERFORMANCE

A significant amount of circuit simulations (PSpice at Maxwell PI and SCREAMER[1] at SNL), field stress modeling (ELECTRO from Integrated Engineering Software), and gain code calculations (Bulkmode[2] and GainCalc V1.0[2] from LLNL) were conducted during the design and operation phase of the FANTM facility. SCREAMER is a fast-running, quick turn-around, user-friendly network code created and used extensively at Sandia for accelerator development. The codes from LLNL generated a time-dependent Average Gain Coefficient (AGC) from an input file consisting of the load power pulse, giving us an accurate estimate of the gain performance without having to drive a real amplifier. The FANTM cable current monitor Rogowski coils and lamp voltage divider monitors were calibrated in situ against certified reference monitors. Both the voltage and current monitors have demonstrated a shot-to-shot consistency of about $\pm 1\%$.[3] Overlays of the PILC and main bank current waveforms have demonstrated very good agreement between the SCREAMER circuit model results and the measured data from FANTM shots. The shot-to-shot repeatability of the FANTM pulses satisfied the energy-spread requirements established for NIF.

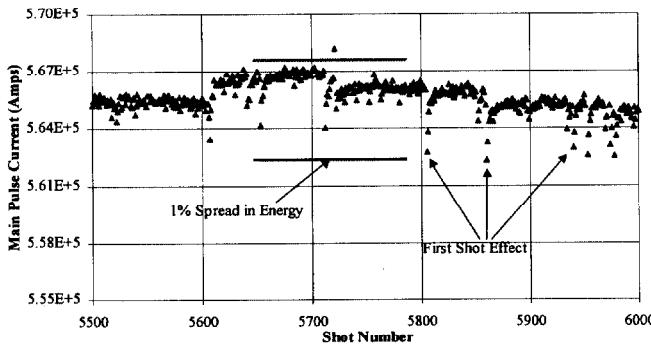


Figure 2. Typical spreads for resistor load current data.

Figure 2 demonstrates the overall variation in peak main bank currents for a 500 shot series with the resistor loads. The different plateaus on the plot correspond to changes in operating conditions, such as the set charge

voltage. The horizontal bars represent the 1%-NIF energy spread requirement. Our power supplies showed a tendency to stabilize to a very repeatable charge voltage after about six shots. This temperature sensitivity causes a "first-shot" effect with lower peak values for the initial shot by about 0.5%. The larger scatter of the "first-shot" data still fell within the allowed energy window.

The FANTM fixed resistor loads and non-linear flashlamp loads produced significantly different waveforms when driven by the same source. Because of the time-varying impedance of the flashlamps and the geometry of the lamp holder, the shape of the power pulse delivered to the lamp pairs is shorter and broader than that of the resistor load. A comparison of the power waveforms from resistor shot #4450 and lamp shot #850 is shown in the overlay of Fig. 3. The best current waveform match occurs when 12 μ H is added to each of the modeled flashlamp loads. Figure 4 compares a

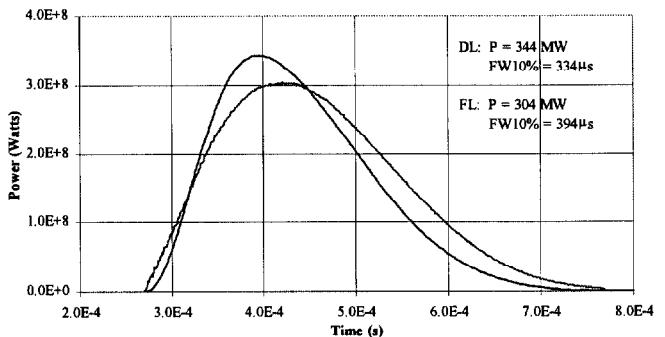


Figure 3. Dummy and flashlamp load power pulses.

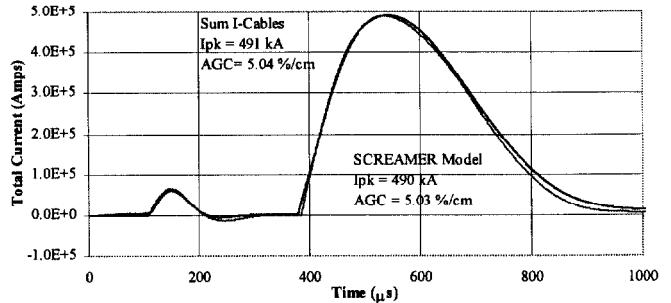


Figure 4. Measured and modeled total currents (L#850).

SCREAMER generated current and the sum of the cable currents for lamp shot #850, in which the bank was charged to 23.8 kV. The simulated result is the lower curve in the plot. The fit is sufficient to produce nearly identical gain calculations of 5.03 and 5.04 %/cm for the model and experiment, respectively. The load impedance model, $V_L = 78.7(I_L)^{1/2}$, for a single series pair of flashlamps is a relationship developed at LLNL.[4] Our resistance model both falls and recovers faster than the measured results indicate for the NIF lamps and matches the data only near the time of peak current.[5]

The lamp-to-lamp and shot-to-shot uniformity of the main pulse is indicated in Fig. 5. The peak currents in three flashlamp pairs represent the highest, average, and lowest of the 20-load assembly over a 1150-shot series. The horizontal bars at the right of the graph show a 3%

spread in energy. The overall lamp-to-lamp spread appears to be about 6%, of which <2% would be due to variations in the monitor calibrations. The individual lamp load scatter is about 1%. The data points indicated by the "No PILC" label are the result of firing the main bank only. The advantage of the PILC pre-ionization pulse in this case is about 600 A or 2.5%.

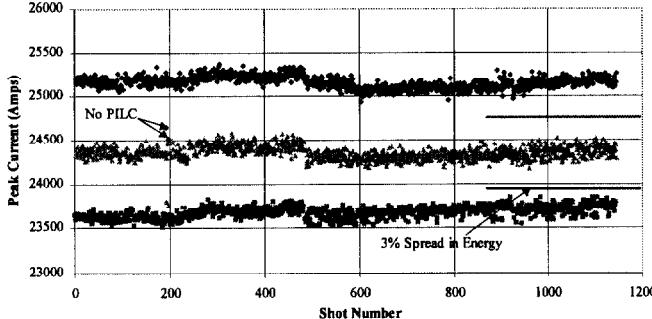


Figure 5. Peak current uniformity for three lamp pairs.

The lamp-to-lamp uniformity within a given shot on FANTM reveals that the relative AGC values of the different pairs are quite repeatable. The lamp differences do not appear to depend on location or geometry. Lamp shot #6153, for example, showed a spread of calculated AGCs from 4.96 to 5.03 %/cm. We ran a series of tests on FANTM in which we varied both charge voltage and number of capacitors. Calculating the median gain from selected shots and displaying it as in Fig. 6 identifies gain contours and estimated scale factors as an aid for tuning future PCS module/cable/amplifier combinations. The resulting voltage impact on gain goes as 62 V/0.01 %/cm. The scaling for capacitance is 1 Cap(310 μ F)/0.06 %/cm. The scaling appears close to linear in this small range of variables. Gain contours associated with modules that drive shorter cables shall shift left and down on the graph.

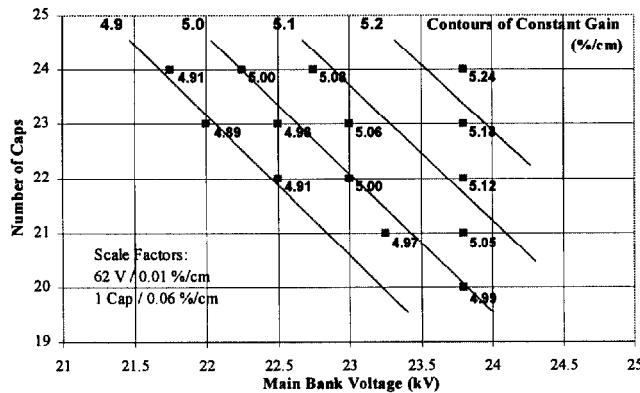


Figure 6. Contours of constant AGC versus V and C.

III. FAULT CONDITIONS

During the course of the FANTM testing, we experienced three major capacitor faults (ranging from 11 to 23.8 kV), one bus fault through a previously damaged dump resistor, and one lamp fault. Some NIF failures have to be expected, but with the risks minimized and

contained. We conducted some intentional faults to carefully diagnose the fault current and voltage levels. Of particular interest are the possible threats to personnel safety or collateral property damage. Every component on FANTM was considered with respect to the fault modes that it would be exposed to, or could cause. As an example, the damping elements were designed by considering the trade-off between the loss they cause for normal operation and the maximum fault current they would pass. An overlay of some of the fault currents that our models predict is shown in Fig. 7. The plotted curves represent a bus breakdown to ground, a capacitor internal short, a cable or feed-connector failure at the top-hat assembly, and a lamp failure or Big-Tee connector short near the load. All the curves except the bus fault are associated with the left-side scale. A bus fault is a failure mode that should be made statistically remote, because it produces the highest current released and potential for the most damage. The curves of Fig. 7 are generated for specific circuit conditions and assuming a fault-path resistance of 5 to 10 m Ω . Experience with planned faults on another prototype bank has indicated higher resistances. The actual peak values could vary significantly (e.g. -50% to +10%). For instance, our one lamp failure drew a fault current that peaked to 45 kA.

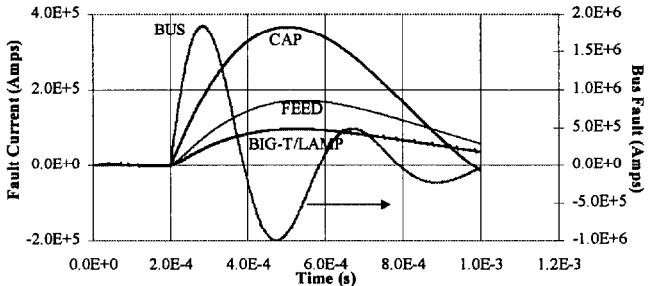


Figure 7. Overlay of possible fault-mode currents.

IV. SUMMARY

We have designed, modeled, fabricated, and tested the First Article NIF Test Module. We will continue evaluating it under normal and fault conditions to make final design refinements. With our experience in developing this Power Conditioning System over its near lifetime-equivalent series of tests, it should meet NIF requirements for performance, cost, and compactness, with the flexibility to exceed some of the specifications.

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